

ENVIRONMENTAL STUDIES

Nighttime light data reveal how flood protection shapes human proximity to rivers

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To understand the spatiotemporal changes of flood risk, we need to determine the way in which humans adapt and respond to flood events. One adaptation option consists of resettling away from flood-prone areas to prevent or reduce future losses. We use satellite nighttime light data to discern the relationship between long-term changes in human proximity to rivers and the occurrence of catastrophic flood events. Moreover, we explore how these relationships are influenced by different levels of structural flood protection. We found that societies with low protection levels tend to resettle further away from the river after damaging flood events. Conversely, societies with high protection levels show no significant changes in human proximity to rivers. Instead, such societies continue to rely heavily on structural measures, reinforcing flood protection and quickly resettling in flood-prone areas after a flooding event. Our work reveals interesting aspects of human adaptation to flood risk and offers key insights for comparing different risk reduction strategies. In addition, this study provides a framework that can be used to further investigate human response to floods, which is relevant as urbanization of floodplains continues and puts more people and economic assets at risk.

INTRODUCTION

Flooding is one of the most damaging natural hazards, and its negative impacts have markedly increased in many regions of the world during the last decades (1, 2). In the period between 1980 and 2014, floods have generated direct economic losses exceeding US\$1 trillion (2014 values) and caused more than 226,000 casualties (3). Increasing global flood losses have been attributed mainly to increasing exposure of people and assets due to rising population and capital at risk in flood-prone areas (2, 4). The future impact of hydrologic events, such as floods and droughts, will strongly depend on the way in which societies continuously adapt and respond to the occurrence of major events (5) and on the risk management approaches they adopt.

Societies can cope with floods by (i) reinforcing structural protective measures, such as levees and flood control reservoirs, to reduce the frequency of flooding; (ii) introducing early warning systems, or adopting a flood-proof building design, to reduce flood vulnerability (6); and (iii) relocating further away from flood-prone areas to reduce flood exposure (7, 8). For relocation processes, such as (planned) managed retreat (7) or (spontaneous) permanent migration (8), people resettle away from high-risk areas to reduce human proximity to rivers and potential flood losses, that is, people and assets at risk.

The purpose of this study is to determine the way in which human proximity to rivers (that is, spatial distribution of human settlements) is shaped over time in relation to occurrences of catastrophic flood events (here inferred as flood damage, in terms of both economic losses and fatalities), in view of different levels of structural flood protection. This type of analysis has not been feasible thus far because traditional census data are typically aggregated at administrative levels and available only at decadal time scales. Thus, census data do not provide useful information at the spatial and temporal scales needed for exploring relationships between human proximity to rivers and flood losses and flood protection levels (9).

An unprecedented opportunity to explore these relationships is offered nowadays by the annual time series of stable nighttime light satellite data (hereafter referred to as nightlight data) (10) that have near-global coverage and a relatively high spatial (1 km) and high temporal (1 year) resolution. Nightlight data have been widely used to study economic activity, land-use change, and settlement dynamics and their impacts on the environment (11–13). Recently, these data have also been used with regard to flood risk. Kocornik-Mina *et al.* (14), for example, used nightlight data as a proxy for economic activity in the period 2003–2008 to explore the recovery of cities after the occurrence of catastrophic flood events. However, the study is limited by its short sample period (2003–2008). Moreover, the authors did not consider different levels of flood protection or flood losses. Ceola *et al.* (15, 16) used nightlight data as proxies for human spatial distribution in the period 1992–2013 to assess the anthropogenic presence along streams at a global scale. They found a higher human concentration near rivers and that flood losses are proportional to nightlight density (15). Yet, their studies did not account for variation in levels of structural flood protection in these locations. Moreover, they considered all rivers, including small streams that cannot realistically generate flooding relevant at the resolution of nightlight data (1 km).

Here, we use freely accessible nightlight data available for the period 1992–2013 (10) to explore the long-term interrelationships between changes in human proximity to rivers, flood occurrences (inferred by flood damage), and flood protection levels in 16 countries across the globe. Specifically, we analyze, for each country, long-term changes in human proximity to medium-to-large rivers (that is, those rivers of sizes most likely to generate large-scale flooding) and assess how these changes relate to flood damage [both economic losses and fatalities, derived from the Emergency Events Database (EM-DAT)] (17) and national levels of structural flood protection (return periods used as standards, ranging from 10 to about 5000 years, derived from Flood Protection Standards) (18). We only use countries that have been affected by river flooding in the period 1992–2013 (according to EM-DAT), when nightlight data are available, and for which reliable information about the range of flood protection

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levels can be directly derived from a recent global inventory assembled by Scussolini *et al.* (18).

To better understand these interrelationships, we also focused on four contrasting case studies or hot spot areas that have different hydroclimatic and socioeconomic contexts, representing both rural and urban areas with different levels of flood protection: Lower Limpopo in Mozambique, Mekong River in Cambodia and Vietnam, Brisbane River in Australia, and Mississippi River at St. Louis in the United States (Fig. 1; see the Supplementary Materials). For example, Limpopo and Mekong are mainly represented by rural areas and have low levels of flood protection, which consists of some minor levees and dikes to protect some agricultural areas (reducing the frequency of flooding to about 1 in 10 years) (18). Both areas experienced devastating floods in 2000. St. Louis and Brisbane are mainly represented by urban areas; St. Louis depends on high flood walls and levees to protect the city and agricultural areas from large floods, while Brisbane depends on the Wivenhoe Dam that was built following the devastating floods in 1974. The structural flood measures in these two cities reduce the frequency of flooding between 1 in 200 years and 1 in 100 years, respectively (18). Devastating flooding was experienced in St. Louis in 1993 and in Brisbane in 2011.

RESULTS

Large-scale analysis

Our large-scale analysis on changes of human proximity to medium-to-large rivers shows that the average distance of human settlements

from rivers has increased for most of the 16 countries (a distance increase ranging from about 100 to 500 m), with Mozambique showing the largest average-distance increase (about 1000 m) during the observation period (1992–2013), while human proximity to rivers appears to be essentially stable in Canada and Netherlands and shows a slight decline in the United States (fig. S1). When exploring how flood occurrences (inferred by flood damage, that is, fatalities and economic losses) influence human proximity to rivers, we found a coincidence (correlation coefficient equal to 0.69) between increasing distance from the river and higher flood fatalities (Fig. 2A). For example, Mozambique, which has experienced the highest number of flood fatalities (normalized to the country's population for the individual years), is also the country where the largest increase in average distance from the river has been observed. Changes of human proximity to medium-to-large rivers were also found to be positively correlated (correlation coefficient equal to 0.39) with economic flood losses [normalized to the national gross domestic product (GDP) for the individual years].

Similarly, Fig. 2B illustrates the relationship between the average change in human proximity to rivers and levels of structural flood protection, that is, a log value of the average return period of structural measures (18), showing in this case a negative correlation (equal to -0.47) between these factors. Mozambique, for example, which experienced the largest change in human proximity to rivers (about a 1000-m increase in average distance from the river), has an average protection standard of 1 (that is, the return period of structural measures is about 10 years), while Netherlands, which has experienced negligible change in human proximity to rivers, has an

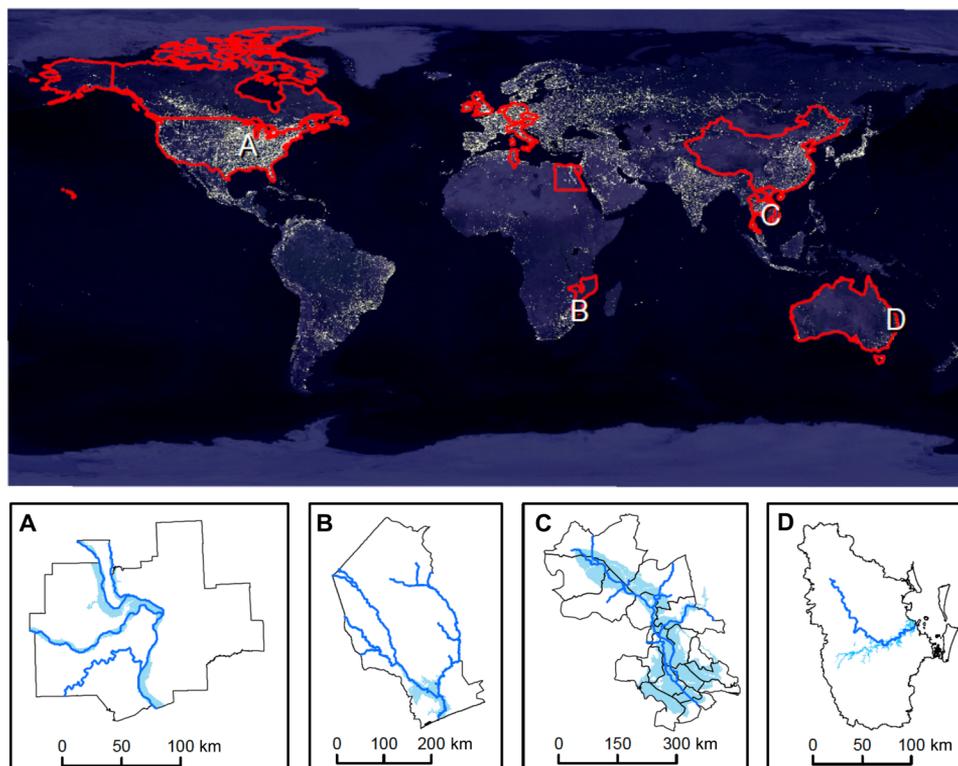


Fig. 1. Study areas. World map showing Earth nightlight data and the 16 large-scale study areas, including the four local hot spots [(A) St. Louis, Missouri; (B) Limpopo; (C) Mekong; and (D) Brisbane] for the local scale analysis and the 16 countries (read borders) for the large-scale analysis. The insets show the main river, flood extent, and the administrative boundaries used for each study area (see the Supplementary Materials). [Earth city lights credit: Data courtesy of M. Imhoff of NASA Goddard Space Flight Center (GSFC) and C. Elvidge of the National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data (NGDC). Image courtesy of C. Mayhew and R. Simmon of NASA GSFC.]

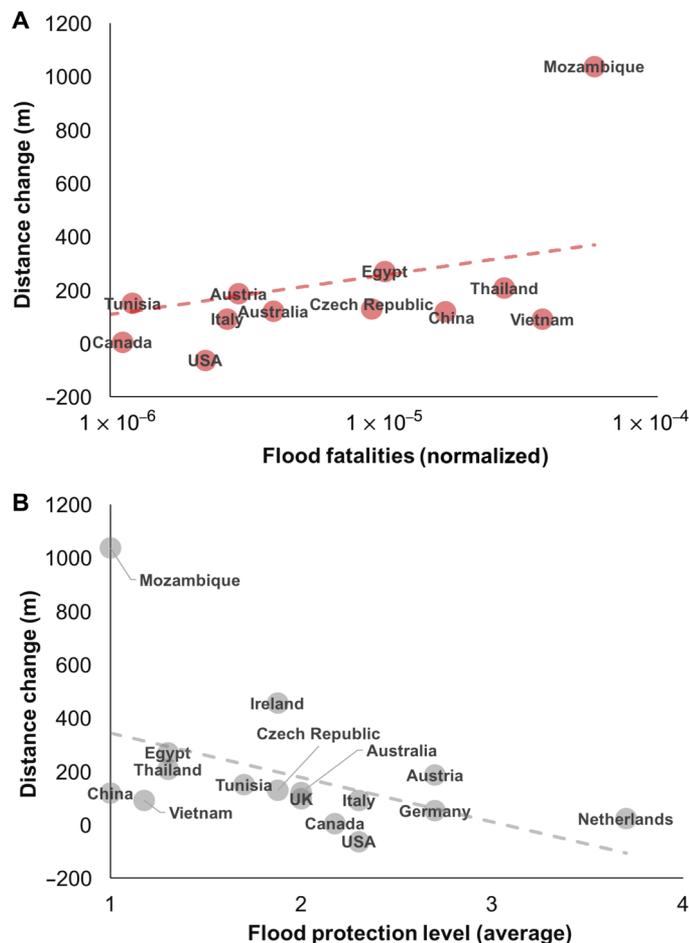


Fig. 2. Large-scale analysis at the country level. Average change of human proximity to rivers in the period 1992–2013 versus (A) normalized flood fatalities, that is, divided by total population for each individual year, and (B) ranges of flood protection level, that is, log value of the return period of structural measures.

average protection standard of 3.7 (that is, the average return period of structural measures is about 5000 years).

Local analysis of hot spot areas

Four hot spot areas were identified based on the outcomes of the large-scale analysis and the availability of local data and information (for example, flood extent maps) about the occurrence of catastrophic flood events, structural flood protection measures, and human response to flooding. In particular, we selected one study area each in Mozambique (Lower Limpopo) and the United States (St. Louis), as these countries are the two end-members in terms of changes in human proximity to medium-to-large rivers (Fig. 2), as well as two hot spot areas in Australia (Brisbane) and Vietnam (Mekong), as these countries exhibit an average change (Fig. 2) and complement the previous two hot spots well to explore human response to floods across different socioeconomic contexts, for example, low- versus high-income countries and rural-to-urbanizing versus highly urbanized areas.

When exploring changes in human proximity to rivers in these local hot spots, we found that the average distance to the river increased for both Limpopo and Mekong to 1800 and 900 m, respectively, over the period 1992–2013 (Fig. 3, A and B). In contrast, hu-

man proximity to rivers changed by only about 100 m each in St. Louis and Brisbane and can therefore be considered to be overall stable (Fig. 3, C and D). In addition to human proximity to rivers, we also studied changes in human spatial distribution within and outside the flooded areas by exploring the fraction of inundated area (from the reference flood extent map; Fig. 1) occupied by nightlights for each study area and year. The Limpopo area exhibits a clear (decreasing) trend, which is consistent with an increasing average distance from the river (Fig. 3). A decreasing trend can also be observed in Mekong following the 2000 flood event, while a more difficult interpretation of these results can be drawn for the St. Louis and Brisbane hot spot areas (Fig. 3).

DISCUSSION

Changes in human proximity to rivers can be driven by multiple factors. Here, we focused on the occurrence of catastrophic flood events (inferred by flood damage) in 16 countries across the globe and found that there is a signal, with both flood fatalities and economic losses at the country scale positively correlated with changes in human proximity to rivers (Fig. 3A). Moreover, we found that this tendency is reduced when high levels of flood protection are in place (Fig. 3B).

Local analysis of four hot spot areas confirms the tendencies highlighted in the large-scale study. Catastrophic flood events may trigger changes in human proximity to rivers (Fig. 3A), as seen in Limpopo and Mekong. This aggregate result can be explained as the combination of spontaneous adaptive processes, such as permanent migration from flood-affected to safer areas, and managed retreat or relocation, such as the “living with floods” programs, which were implemented after the flood events, including resettlements out of the flood-prone areas (19). For example, about 200,000 households were relocated from flood-prone provinces to flood-protected areas in the Mekong Delta following the 2000 flood event. The decrease in human settlements close to the river may also have contributed to reduced exposure to future flood events. Both study areas were again affected by major flooding events (2013 for Limpopo and 2011 for Mekong) with hydrological impact similar to that of the 2000 flood events, but with a significant reduction in fatalities, number of people affected, and economic losses in the second event; for example, the number of fatalities was reduced by 83 and 77% for Limpopo and Mekong, respectively (17, 19).

On the other hand, we also see that this tendency is reduced when high levels of flood protection are in place (Fig. 3B), as seen in Brisbane and St. Louis. For St. Louis, we see no significant change in human proximity following the flood event in 1993. However, following the 1993 flood event, there was a buyout program undertaken to help affected people move out of the floodplain. Meanwhile, damaged levees were quickly repaired, and despite the fact that the area experienced one of the costliest and most devastating floods in the United States, there have been more structures built on the floodplain in the St. Louis area than ever before. As the flood in Brisbane occurred toward the end (2011) of the observation period (1992–2013), changes in human proximity can only be explored for a couple of years. Yet, Brisbane experienced a devastating flood event in 1974, and since then, the area has continued to develop on the floodplain without significant changes in the average distance to rivers. This can be attributed to the sense of security caused by the presence of the Wivenhoe flood control reservoir (see Materials and Methods).

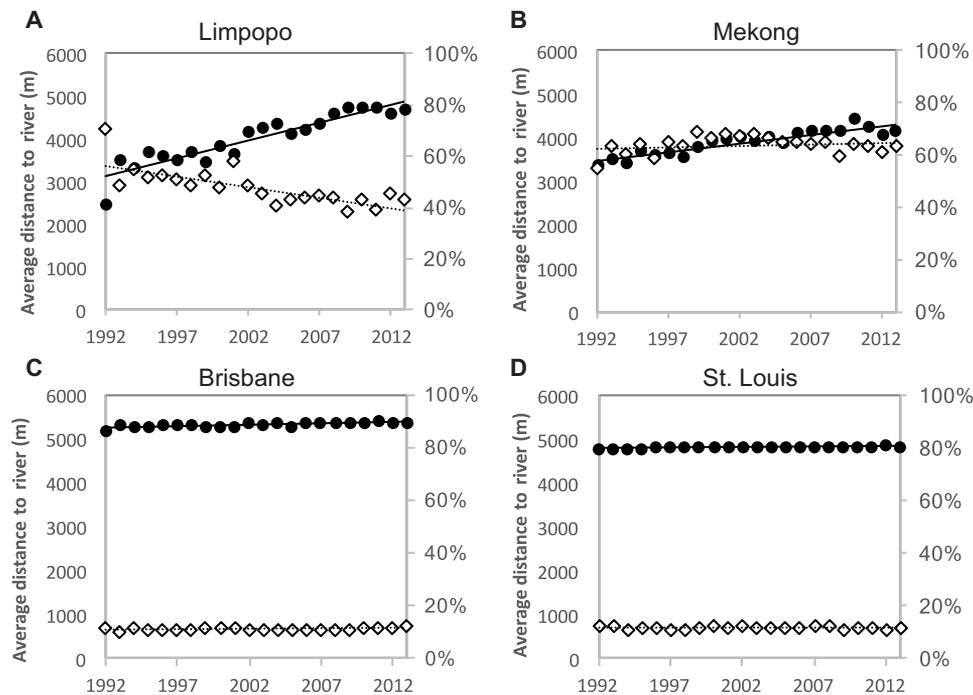


Fig. 3. Human proximity to rivers. Average distance of human settlements to the river (left axis, full black dots) and fraction of inundated area occupied by nightlights (right axis, empty diamonds), with a distance threshold of 10 km from the river, between 1992 and 2013 for Limpopo [average distance change, 1800 m (A)], Mekong [average distance change, 900 m (B)], Brisbane [average distance change, 140 m (C)], and St. Louis [average distance change, 70 m (D)].

Brisbane and St. Louis are, in our study, representative of high-income countries that continue to heavily rely on structural protective measures. Response to flood events often consists of repairing or reinforcing levees or changing reservoir operation rules, with people quickly resettling in affected areas, and development seems to increase behind structural measures, amplifying motivation for its continuation. Although these residents will be protected from frequent flooding, total protection is not possible, and therefore, they remain exposed to future low-probability but catastrophic-impact events. This “levee effect” has been questioned by various scholars starting with Gilbert White in the 1940s (8, 20–25). A number of high-income countries (including the United States and Australia) have recently started programs to remove structural protective measures and include aspects of living-with-floods strategies, not only to cope with levee effects but also to alleviate their negative effects on biodiversity and ecological functions (26, 27). Yet, these programs have had limited success on societies, as resettling away from high-risk areas or avoiding additional development in flood-prone areas often encounters legal challenges (8). The results presented here, at both large and local scales, suggest that this policy shift may still have a long way to go. One obstacle is due to the locked-in conditions emerging once high levels of flood protections are put into place, which means that, for instance, building levees may promote further urban expansion, industrialization, and economic growth in floodplain areas and may thus motivate the continuation of even stronger structural protective measures, which then will make it difficult to entirely shift into living-with-floods strategies.

Implications and further research

The outcomes of our study open up new horizons in various scientific fields, from the study of human-environment interactions to the

assessment of flood risk under climate and socioeconomic changes. The observed relationships between flood occurrences, flood protection levels, and human proximity to rivers can be used as a benchmark to evaluate agent-based [for example, (28, 29)] or conceptual models of human-flood interactions [for example, (21, 30–32)], thereby substantially improving the way in which we simulate flood risk in a world with rising population, economic growth, and a changing climate (33, 34).

The results presented here are unavoidably limited by the time span of nightlight data (1992–2013) used in our analysis, as more complex spatiotemporal dynamics of human settlements may emerge at longer time scales. Moreover, while the outcomes apply to the 16 countries analyzed here, the study provides an original framework that can be extended to further quantify global patterns of human response to floods. For example, one can exploit the growing availability of worldwide information, such as (i) Earth observation tools, for example, flood observatories (35), to detect timing and extent of flood events; (ii) global databases of flood losses (17); (iii) combination of nighttime and daytime lights (36) to explore spatiotemporal changes of human settlements; and (iv) worldwide archives of flood protection levels (18) to detect areas that heavily rely on structural measures.

Moreover, this study reveals interesting aspects of human response to damaging flood events. The large-scale analysis indicates that flood occurrences can trigger decreasing human proximity to rivers but mainly only in those societies that do not strongly rely on structural protective measures (Fig. 3B). This result is relevant as urbanization of flood-prone areas continues and puts more people and economic assets at risk of flooding. Flood risk adaptation and flood risk reduction continue to be high on national and international agendas as demonstrated by several major policies recently initiated or renewed

in this field, such as the Sustainable Development Goals, Conference of the Parties 21, and the Sendai Framework for Disaster Risk Reduction. Our study suggests that, before advocating for higher levels of flood protection (37, 38), one has to carefully consider the long-term consequences associated with structural protective measures, that is, emergence of locked-in conditions in which flood exposure becomes essentially impossible to reduce. These conditions can be considered affordable in certain contexts, such as in Netherlands, but they might result as unsustainable in other areas. Moreover, while protection measures reduce the frequency of flooding events today, we cannot precisely predict future flood levels, especially in view of climate and socioeconomic changes, and total protection is impossible anyway.

MATERIALS AND METHODS

Study areas

In our large-scale analysis, we identified 16 countries that have been affected by river floods in the period 1992–2013 (Fig. 1), according to EM-DAT (17), and for which reliable information about the range of flood protection levels could be directly derived from a recent global inventory assembled by Scussolini *et al.* (18). These countries range from low- to high-income countries, and protection levels range from about 10 years (Mozambique) to about 5000 years (Netherlands) (see, for example, Fig. 2). In addition to the large-scale analysis, we identified four hot spot areas or case studies that have experienced damaging flood events over the past two decades and have different hydroclimatic and socioeconomic contexts, representing both rural and urban areas with different levels of flood protection. The four hot spot areas are located on four different continents: Lower Limpopo River in Mozambique, Lower Mekong River in Vietnam and Cambodia, Brisbane River in Australia, and Mississippi River at St. Louis in the United States (Fig. 1).

Lower Limpopo River in Mozambique has a semi-arid climate and has a history of long drought periods interrupted by flood events. In February 2000, southern Mozambique experienced the biggest flood ever recorded (Fig. 1A). At least 800 people died, more than 4.5 million people were affected, and economic losses were estimated to be more than US\$541 million [ref. (17); inflation corrected value 2016]. In January 2013, the Limpopo River basin was again affected by devastating floods. Although the 2013 flood recalled the 2000 flood in terms of hydrological impact, the event produced less damage. The number of people affected and the economic loss decreased by 93 and 95%, respectively, compared to the 2000 event [ref. (19); inflation corrected values 2016]. This can be attributed to the fact that communities and individuals in Mozambique, as well as the affected authorities, have learned a valuable lesson from the severe 2000 flood event. For instance, flood risk programs were implemented with focus on education and resettlements (19).

The Lower Mekong River at the border of Cambodia and Vietnam has a tropical monsoon/savanna climate. The Mekong Delta is regularly flooded during the Asian monsoon period, but in 2000 and 2011, exceptionally high floods occurred, which caused significant damage in the region. The 2000 flood event (Fig. 1B) caused 843 fatalities, and economic losses were estimated to be more than US\$590 million (2016 inflation-corrected value) (17). For the 2011 event, the number of fatalities was 77% less than that in 2000 (17). This can be partly attributed to multiple risk reduction actions taken after the 2000 event. This included, for example, resettlements

of rural population in the delta, where about 200,000 households were relocated from flood-prone provinces to flood-protected areas (19).

Brisbane River in Queensland, Australia, has a humid subtropical climate. Urban areas are built on its floodplain, which has a history of damaging flood events. The largest flood in the 20th century occurred in 1974, which remains the most severe example of urban flooding in Australia (39). In January 2011, major flooding occurred throughout most of the Brisbane River basin (Fig. 1C). The 2011 flood event caused 24 fatalities, more than 200,000 people were affected in Queensland, and economic losses were estimated to be AUS\$1 billion (39, 40). This catastrophic event surprised local people as Brisbane was considered “flood-proof” after the construction of the Wivenhoe flood control reservoir (41). Since the 2011 flood event, the Brisbane City Council has undertaken a significant work program to act on the lesson learned, including recommendations on insurance, urban planning, and reservoir operations.

St. Louis, Missouri, located at the confluence of Mississippi and Missouri rivers, has a humid continental climate. In 1993, the area experienced one of the costliest and most devastating floods in the United States (Fig. 1D). The Mississippi and Missouri flood event caused 48 fatalities, and more than 50,000 homes were damaged as levees failed or were overtopped. The economic losses from farmland, towns, and transportation routes being destroyed approached US\$20 billion (42). The flood in 1993 was caused by intense and continuous rainfall together with already wet soil conditions. Most of the levees and floodwalls in urban areas withstood the flood, while many agricultural levees failed or were overtopped (43). Following the 1993 flood event, levees damaged by the flood were repaired, and a buyout program was undertaken in Missouri to help affected people move out of the floodplain. However, since then, there have been more structures built on the floodplain in the St. Louis area than ever before; that is, more than 28,000 new homes and commercial and industrial parks have been developed on land that was under water in 1993. This new infrastructure heavily depends on new enlarged levees to hold back floodwaters of the Mississippi and Missouri rivers.

Human proximity to rivers

Nightlight data were used in the study as a proxy for spatiotemporal changes of human settlements (10). To assess how human spatial distribution (for example, relocation patterns) is shaped over time in relation to flood events and in view of different levels of structural flood protection, we examined changes in nightlights and the proximity to the main river over time. Our method built on Ceola *et al.* (16) and included the following novel aspects: (i) We referred only to human proximity to rivers having a contributing area above 5000 km², excluding smaller streams that cannot realistically generate flooding events relevant at the resolution of nightlight data (~1 km); (ii) we explicitly took into account the national levels of structural flood protection (return periods used as standards, ranging from 10 to about 5000 years, derived from FLOPROS) (18); and (iii) we complemented analysis of human proximity to rivers with the fraction of inundated area (from the reference flood; Fig. 1) occupied by nightlights for each hot spot area and year to explore human spatial distribution within and outside the flooded area.

Annual time series of stable nightlights (Version 4) as satellite images from the Defense Meteorological Satellite Program, Operational Linescan System are freely available as raster format from

the NOAA NGDC (11) and are available from 1992 to 2013. Stable nightlights record light intensities from cities and towns, while background noise (for example, sunlit and moonlit data) and temporary light sources such as fires are removed. The data set is near global (from 75°N to 65°S and from 180°W to 180°E), and the spatial resolution is 30 arc sec (0.00833° or ~1 km at the equator). Nightlight images are from six different satellites operating during 1992–2013 (table S3), and for years where two satellites were simultaneous in operation, an average value was determined. Each nightlight satellite image contains annual averaged digital number values ranging between 0 (complete darkness) and 63 (bright areas, that is, cities and towns). Because of the absence of onboard calibration and lack of intersatellite calibration, we used an intercalibration method applied in previous papers [for example, (44)] to make the annual averaged satellite imagery comparable. There are some limitations of using nightlight data, including pixel (light) saturation in highly populated urban areas and blooming effect (that is, overestimation of lit area) due to coarse resolution and reflectance from, for example, water bodies in large metropolitan areas, as well as insufficiency in capturing settlements with little or no electricity (that is, rural areas in Africa). Threshold techniques have been used in previous studies to overcome the former issue with overestimation and saturation effects, for example, (45). However, threshold methods are not always applicable in developing countries where average nightlight density is weaker. Hence, we did not apply any threshold techniques in our study, considering that two of the study areas are in developing countries. Here, we limited the influence of these effects by considering long-term changes rather than focusing on individual years. For shorter time spans, one can cope with these issues by, for example, combining nightlight data with daytime data (36).

We used HydroSHEDS river network data (46) (<https://hydrosheds.cr.usgs.gov/index.php>) provided by the U.S. Geological Survey to assess human proximity to rivers. HydroSHEDS is based on elevation data of the Shuttle Radar Topography Mission that has been hydrologically conditioned (for example, void-filled and stream-burned). The river network data have a spatial extent between 62°N and 55°S and between 180°W and 180°E and a spatial resolution similar to the nightlight data (30 arc sec or 0.00833°). Given the focus on river flooding and the resolution of nightlight data, we considered only perennial rivers (continuous flow all year round) that have a contributing area of $\geq 10,000$ km² for the large-scale analysis and ≥ 5000 km² for analysis of the hot spot areas.

To identify spatial and temporal changes in human distribution and proximity to rivers, nightlight data were divided into 11 distance-from-river classes ranging from 0 to 10 km with a 1-km stepwise increase (as 1 km is the resolution of nightlight data). A 10-km buffer was defined based on the general width of the floodplains; hence, the area prone to floods (see the Supplementary Materials for further details). First, we analyzed the human spatial distribution across distance classes by calculating the absolute sum of nightlights for each distance class for each study area and year (16). This was done at a country level for the large-scale analysis and within administrative areas for the local hot spots (table S2). Second, we defined human proximity to rivers, which is the weighted average of the distance class total luminosity, where the relative sum of nightlights (extracted from absolute values) represents the weight [see mathematical details in (16)] and where the results were aggregated at the country level for the large-scale analysis. Figure S1 shows changes of human proximity in the period 1992–2013 for all 16 countries. In

addition to human proximity to the river, we also explored the fraction of inundated area (from the reference flood; Fig. 1) occupied by nightlights for each hot spot area and year.

For large-scale analysis, we also explored how flood occurrences (inferred by flood damage, that is, fatalities and economic losses) influence human proximity to rivers. Data on flood fatalities (normalized to the country's population for the individual years) and economic losses (normalized to the national GDP for the individual years) were extracted from EM-DAT (17). We also explored the average change of human proximity to rivers with levels of structural flood protection, that is, log value of the average return period of structural measures (18).

To test the robustness of the results, we performed a systematic resampling experiment with a leave-one-out approach. One of the countries was removed from the data set, and the correlation coefficient between the average changes of river proximity and (i) flood protection levels, (ii) normalized flood losses, and (iii) normalized flood fatalities, respectively, was recomputed. This was repeated 16 times, leaving out 1 of the 16 countries at a time. Figure S2 shows the first, second (median), and third quartile of the three correlation coefficients, highlighting the robustness of the correlations explored in this study.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/4/8/eaar5779/DC1>

Supplementary Materials

Fig. S1. Large-scale analysis: trends in human proximity to rivers.

Fig. S2. Results of the robustness test: leave-one-out approach.

Table S1. Satellite imagery used for estimation and delineation of maximum flood extent.

Table S2. Administrative areas considered for the four study areas that were affected by the occurrence of flooding.

Table S3. Observation year, satellite number, and nightlight satellite data set.

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